



# Thermal Signature Identification System (TheSIS)

*a Spread Spectrum Temperature Cycling Method*

Scott Merritt, Brian Bean

NASA-GSFC/554

SPIE Photonics West 2015  
9369-22



# Goals & Key Features of TheSIS



## GOALS

- 1) Prepare for multivariate modern control loop design using detailed models of device and system dynamics, i.e. “thermal signatures”.
- 2) Capture the maximum thermal performance information in the minimum time.

## KEY FEATURES

- 1) Measure the thermal signatures of optoelectronic components to direct sequence spread-spectrum temperature cycles,
- 2) Model the thermal signatures, and
- 3) Select the most likely model per the Akaike Information Criterion (AIC).
- 4) Analyze parameter variability and develop multivariate Figures of Merit.

Using the AIC-tested model and parameter vectors from TheSIS, one can analyze changes in model parameters, detect subtle reversible shifts in performance, investigate the cause of instabilities or irreversible changes in component or subsystem performance, e.g. aging, and select high-performing components on a multivariate basis, i.e. with multivariate Figures of Merit (FOM). We show examples of the TheSIS methodology for passive and active components and systems, e.g. fiber Bragg gratings (FBGs) and DFB lasers with coupled temperature control loops.



# Applications

---



- EO Component, Subsystem, and System Evaluation (this talk)
- Electronic Component Evaluation
  - e.g. Oscillators, Crystals, Frequency References
- Reliability/Failure Analysis,
  - e.g. modify Thermal Vacuum (TVAC) cycling profiles to include System Identification (SI) via direct sequence spread spectrum “dither”.
- Efficient Thermal cycling and Control Loop SI Problems
  - e.g. Tuning PID or other control loops -> “plant” models
  - e.g. Polymerase Chain Reaction (PCR) control



# Three Perfect Barker Codes

Use for : **Short Direct Sequence Spread Spectrum**



Barker 3: + + -

Barker 7: 

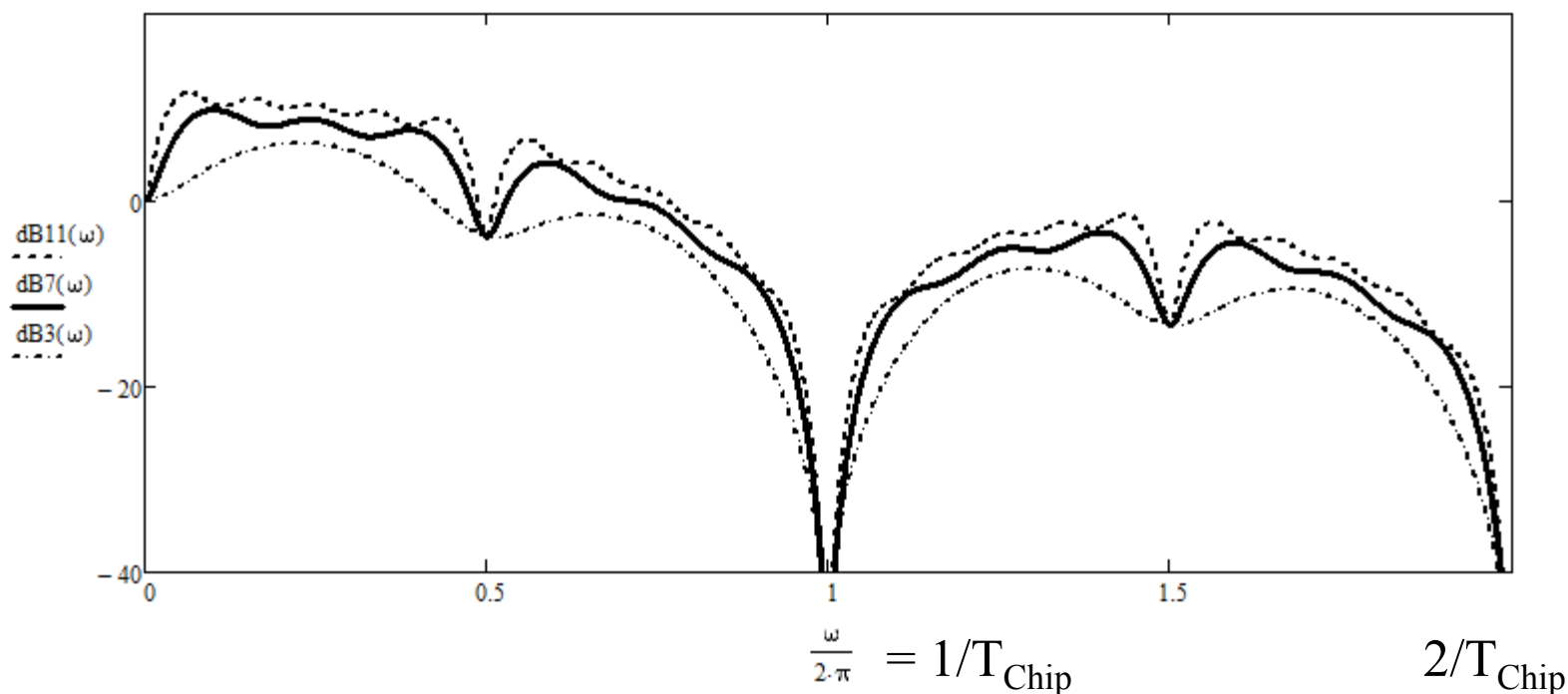
+	+	+	-	-
---	---	---	---	---

 + -      Each + or - is a “Chip”

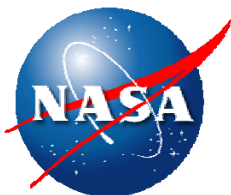
Barker 11: 

+	+	+	-	-
---	---	---	---	---

 - + - - + -



Note: the spectrum of the other perfect code, Barker 2 +-, is not shown



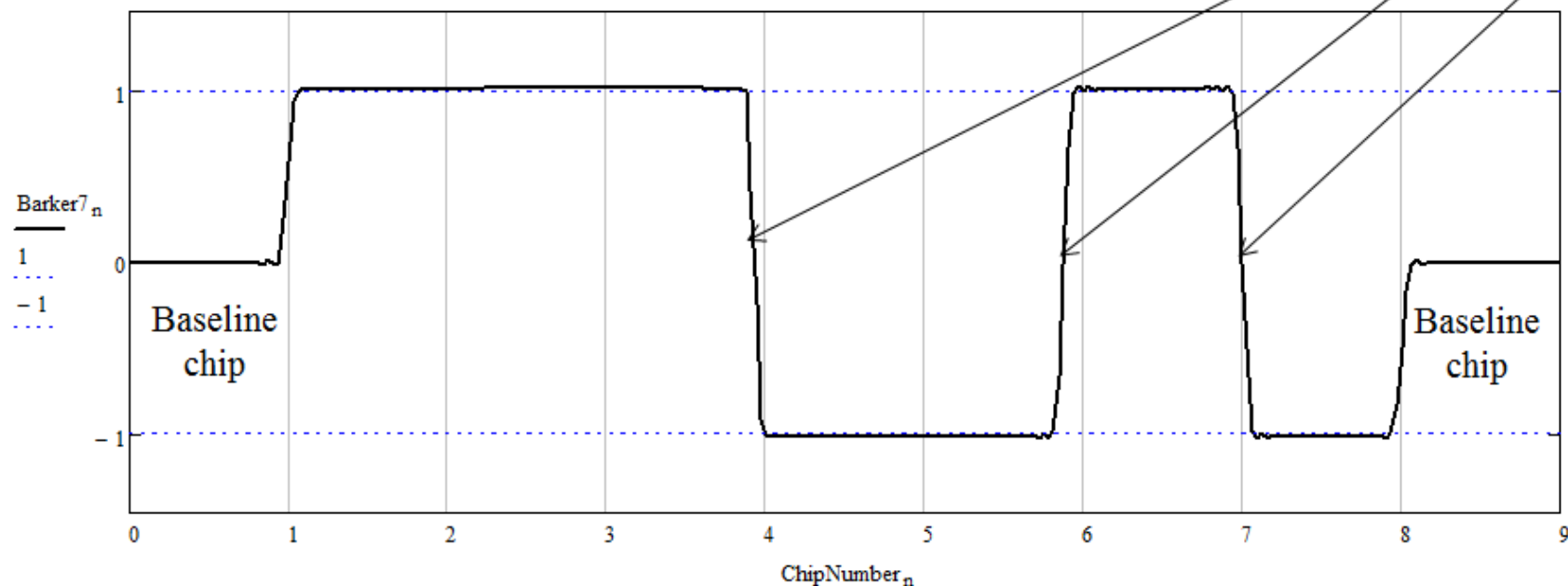
# Modified Barker 7 Profile

(7 sub-intervals = "Chips")



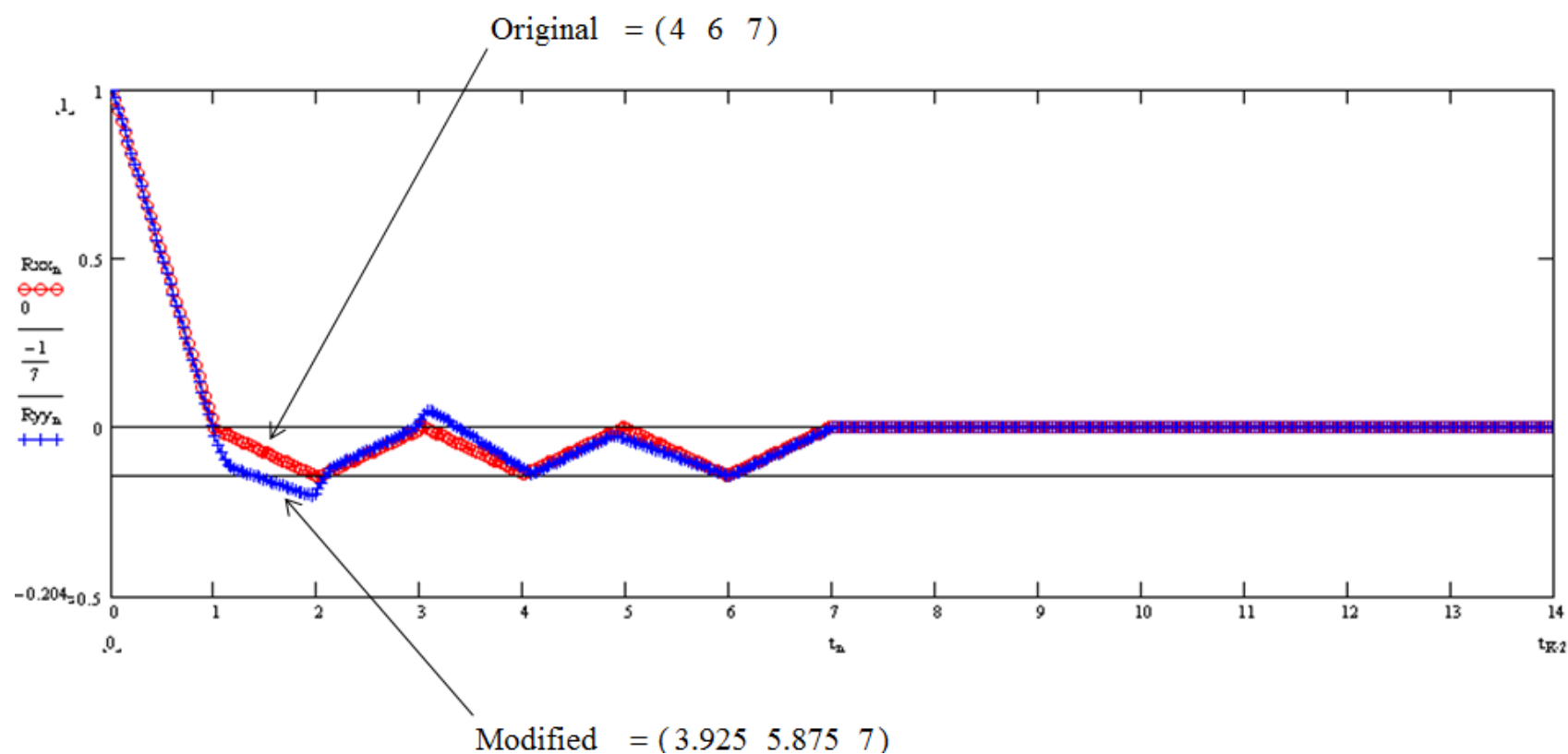
Original = (4 6 7)

Modified = (3.925 5.875 7)





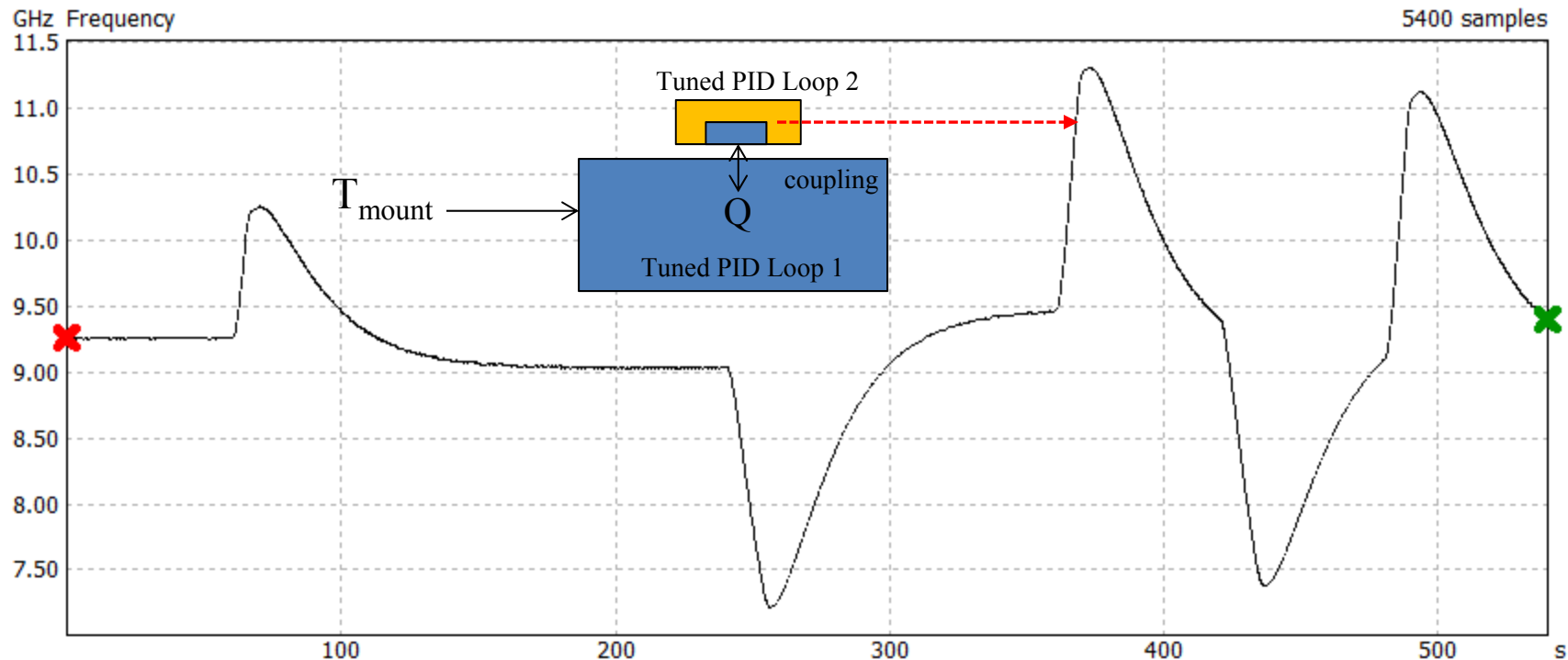
# Autocorrelation of Barker 7 and Modified Barker 7





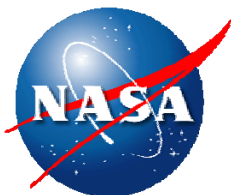
# Application: Active Optoelectronic System

## DFB Environmental Perturbation, $T_{\text{mount}}$

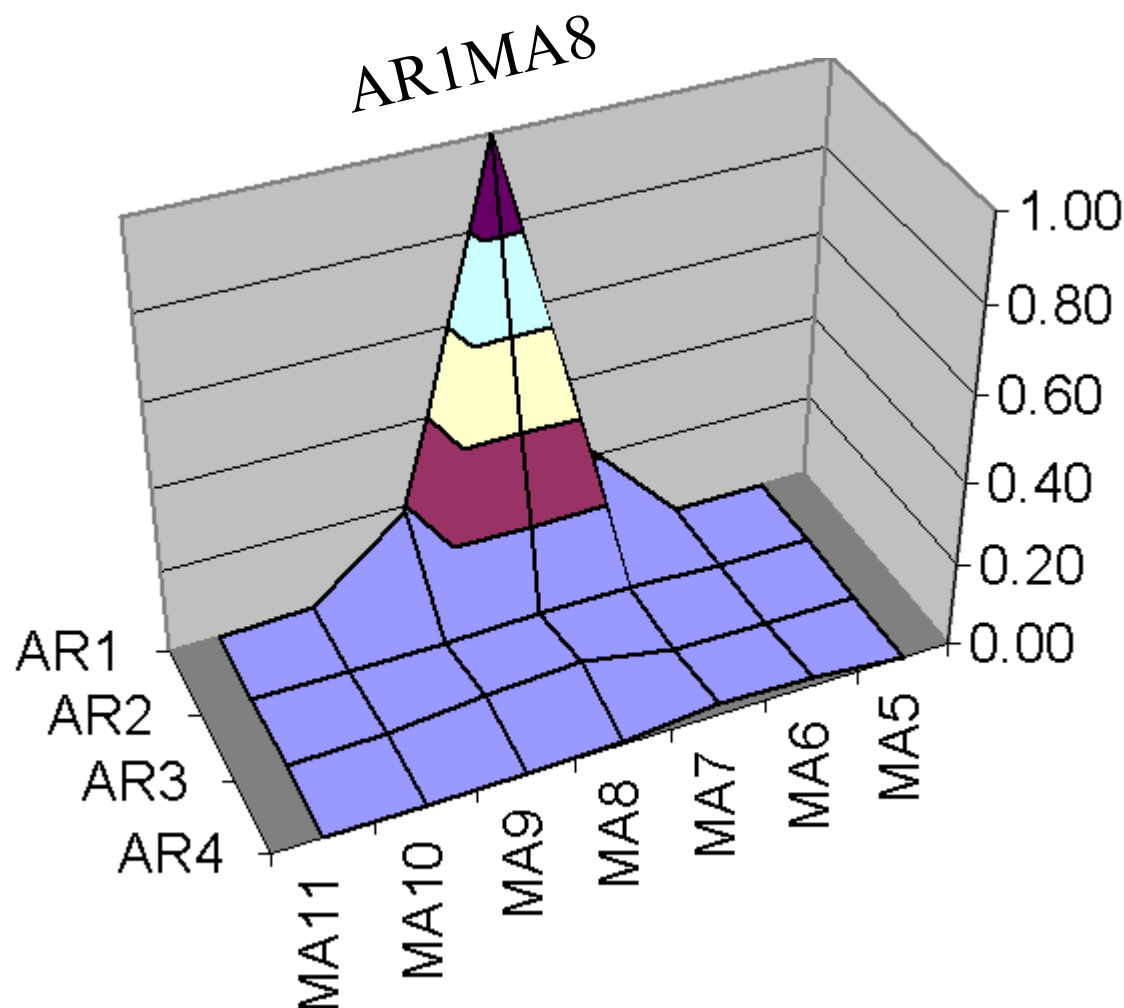


Note Frequency is from Laser Heterodyne method with the reference laser or LO at a higher frequency than the device under test (DUT). Therefore, as displayed here, a frequency increase corresponds to a redshift of the DFB laser.

$$T_{\text{chip}} = 1 \text{ minute}$$



## A Comparison of Autoregressive Moving Average (ARMA) Models of DFB Laser Dynamics using the Akaike Information Criterion (AIC)



$$e^{-(AIC - AIC_{min})/2}$$

is the likelihood of a  
given model relative to  
the most likely model.



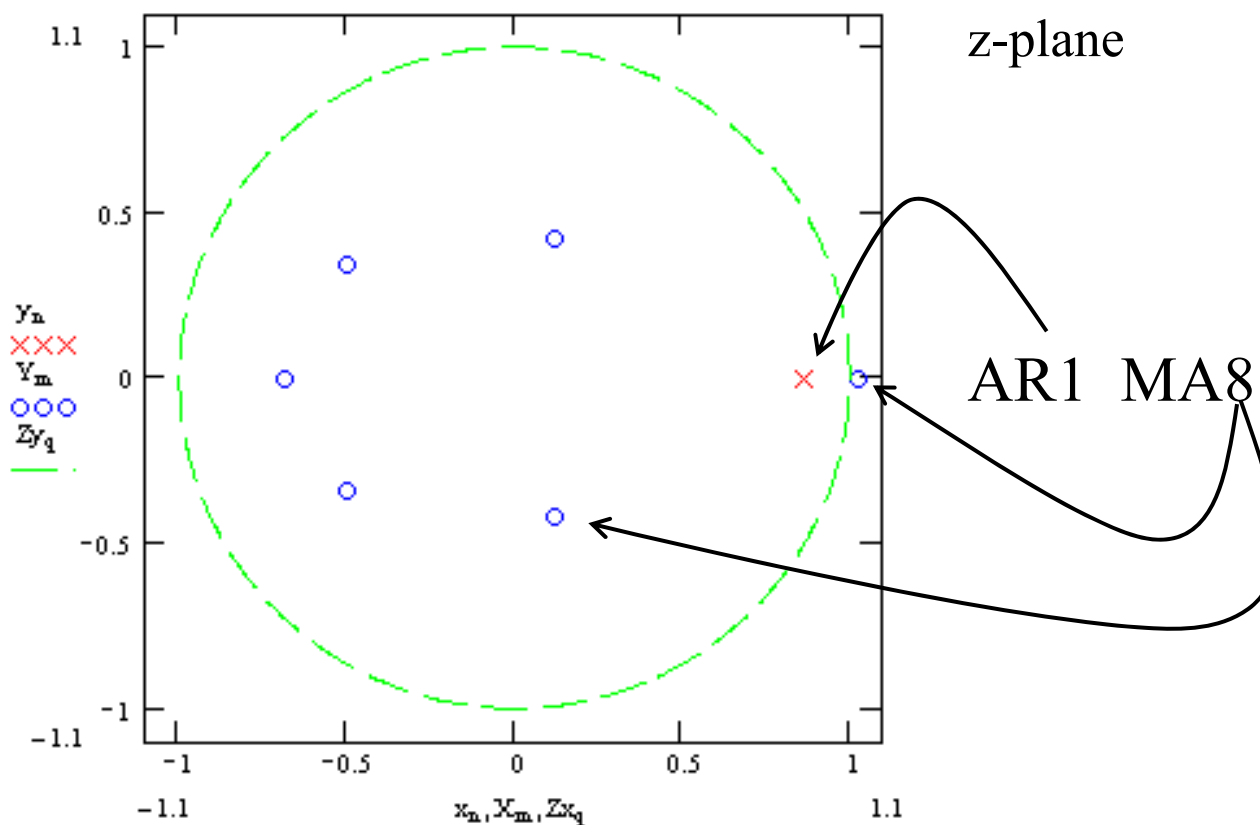


# Pole and Zeros of (*DFB Laser + Laser TEC*) Response to Mount TEC set point changes



(AR1MA8; one of the seven Zeros is not shown; (at -3.48) )

Sampling Period,  $T=4.5$  seconds





# Application: Passive Optoelectronic Component

## TheSIS Analysis of Fiber Bragg Gratings

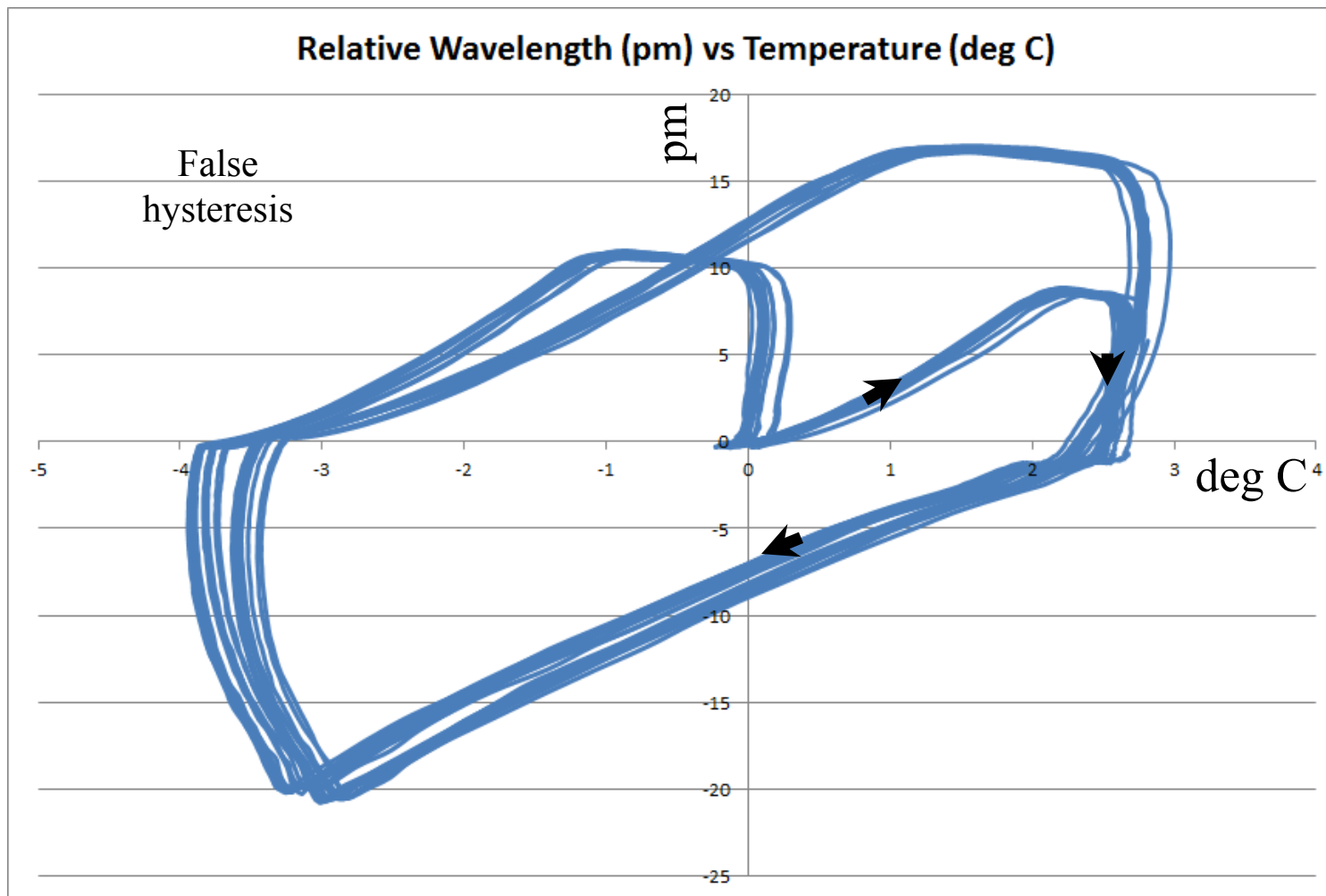
---



1. False Hysteresis
2. Recursive peak finding algorithm  
( $\lambda_c$ , Insertion Loss (dB), Reciprocal Bandwidth Squared)
3. Modified Barker 7 Cycling
4. FBG AR3MA2 Poles and “thermality zero” for MA2 models
5. Stability of Poles and “thermality zero”,  $Z_T$
6. Temperature coefficient of center frequency,  $\alpha$ .
7. Contrast conventional vs TheSIS temperature cycling
8. Multivariate selection metric



# Center Wavelength Deviation



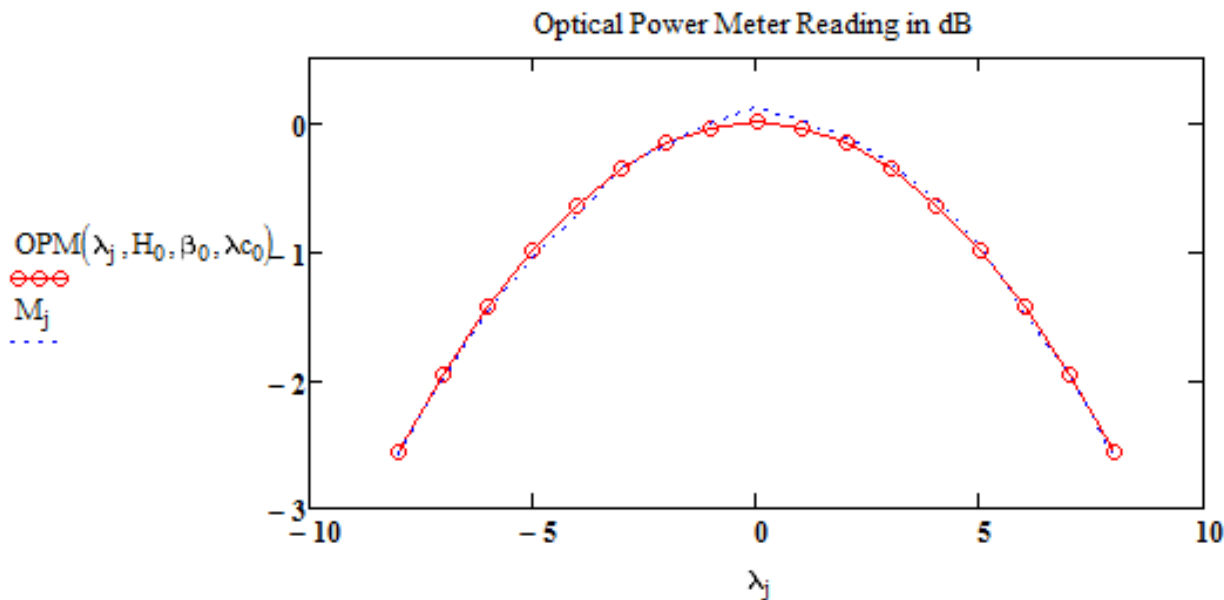
# Peak Finding Recursion



## MODEL

$$\text{OPM}(\lambda, H_0, \beta, \lambda_c) := H_0 + \beta \cdot (\lambda - \lambda_c)^2$$

Parabolic "near" the peak, at  $\Lambda_c$ ,  $\beta$  is negative



$M_j$  are the measured  
Optical Power values.

J is the number of samples  
per spectrum.  $j = 0 \dots J-1$

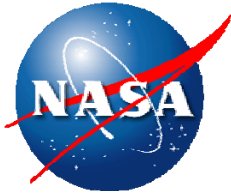
M spectra collected at  
T=4.5 second intervals  
and interpolated to 4  
seconds.

$H_0$  is insertion loss

$\beta$  is inverse bandwidth squared parameter

$\lambda_c$  is center Wavelength

Samples of  $M$  can be collected individually, e.g. via laser heterodyne, and in any order.



# Peak Finding Recursion



$$P(H, \beta, \lambda_c) := \sum_j \left[ M_j - \left[ H + \beta \cdot (\lambda_j - \lambda_c)^2 \right] \right]^2$$

Performance Function: Find H, Beta, and Lambda\_C (not initial values); After at least one **iteration**, REPLACE initial values H0, Beta\_0, and Lambda\_C0 values with H, Beta, Lambda\_C below; i.e. the program is **recursive and, optionally, iterative**.

$$H := \frac{\sum_j \left[ M_j - \beta_0 \cdot (\lambda_j - \lambda_{c0})^2 \right]}{J + 1} \quad \text{dBm}$$

$$\beta := \frac{\sum_j \left[ (M_j - H_0) \cdot (\lambda_j - \lambda_{c0})^2 \right]}{\sum_j (\lambda_j - \lambda_{c0})^4} \quad \text{dBm/pm}^2$$

$$\lambda_c := \lambda_{c0} - \frac{\sum_j \left[ \left[ M_j - H_0 - \beta_0 \cdot (\lambda_j - \lambda_{c0})^2 \right] \cdot \beta_0 \cdot (\lambda_j - \lambda_{c0}) \right]}{\sum_j \left[ 2 \cdot \beta_0^2 \cdot (\lambda_j - \lambda_{c0})^2 - \left[ M_j - H_0 - \beta_0 \cdot (\lambda_j - \lambda_{c0})^2 \right] \cdot \beta_0 \right]} \quad \text{pm}$$

$$\beta := \frac{-12}{BW^2}$$

BW = 3dB  
bandwidth

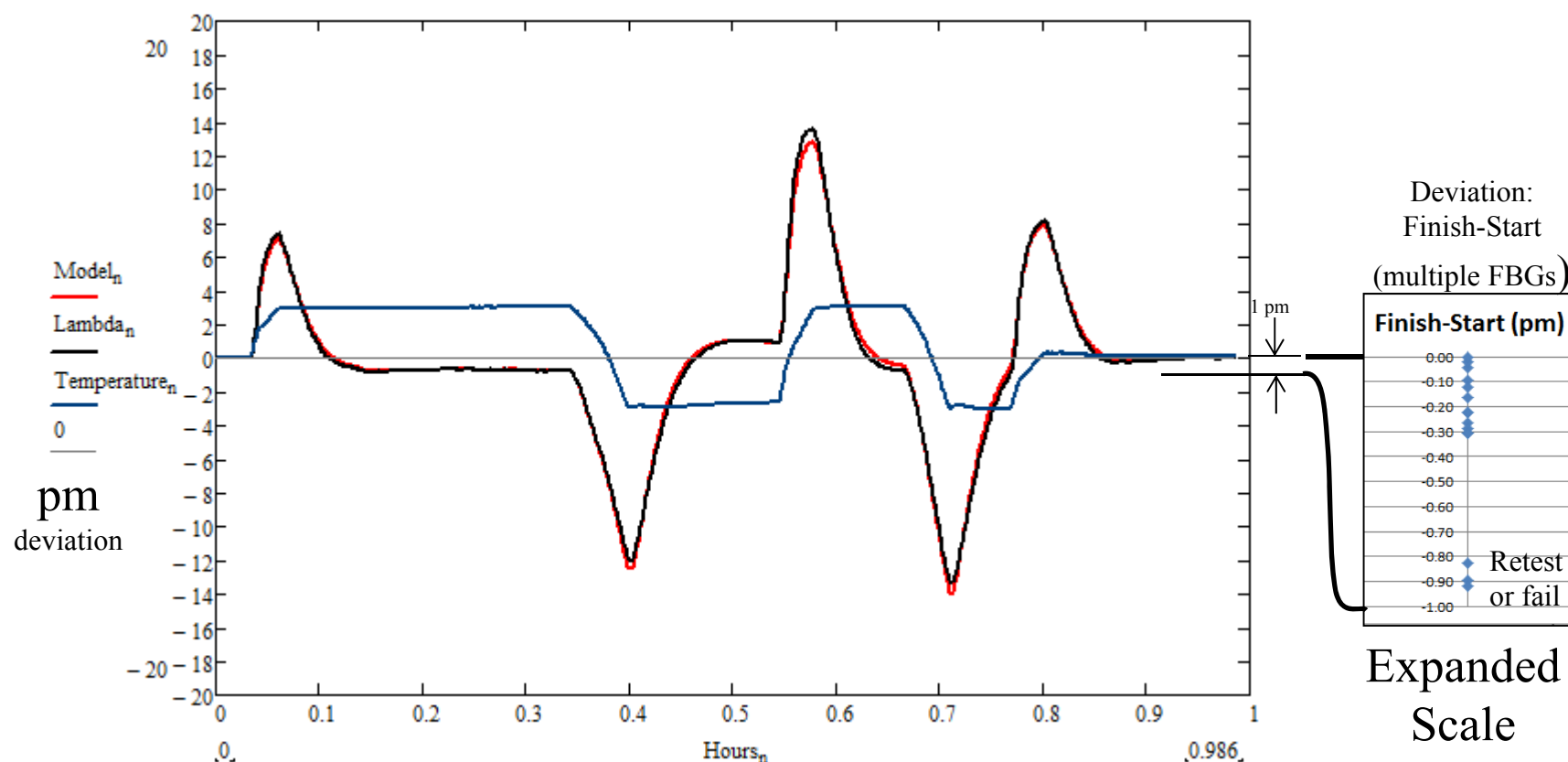
$$\sigma := \sqrt{\frac{-5}{\ln(10) \cdot \beta}}$$

Gaussian  
parameter

$H \rightarrow$  Insertion Loss,  $\beta \rightarrow$  Bandwidth<sup>-2</sup>,  $\lambda_c \rightarrow$  Center Wavelength  
(the zero subscript denotes the value of the previous recursion)



# A Barker 7 TheSIS Cycle for Fiber Bragg Gratings (FBG)



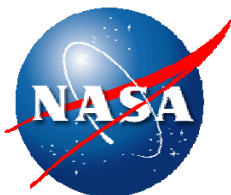
Temperature (blue) in deg C. AR3MA2 Model (red)

Typical AR3MA2  
Parameter Vector

AR3			MA2	
B1	B2	B3	A0	A1
1.52548	-0.26380	-0.26980	0.81490	-0.81700

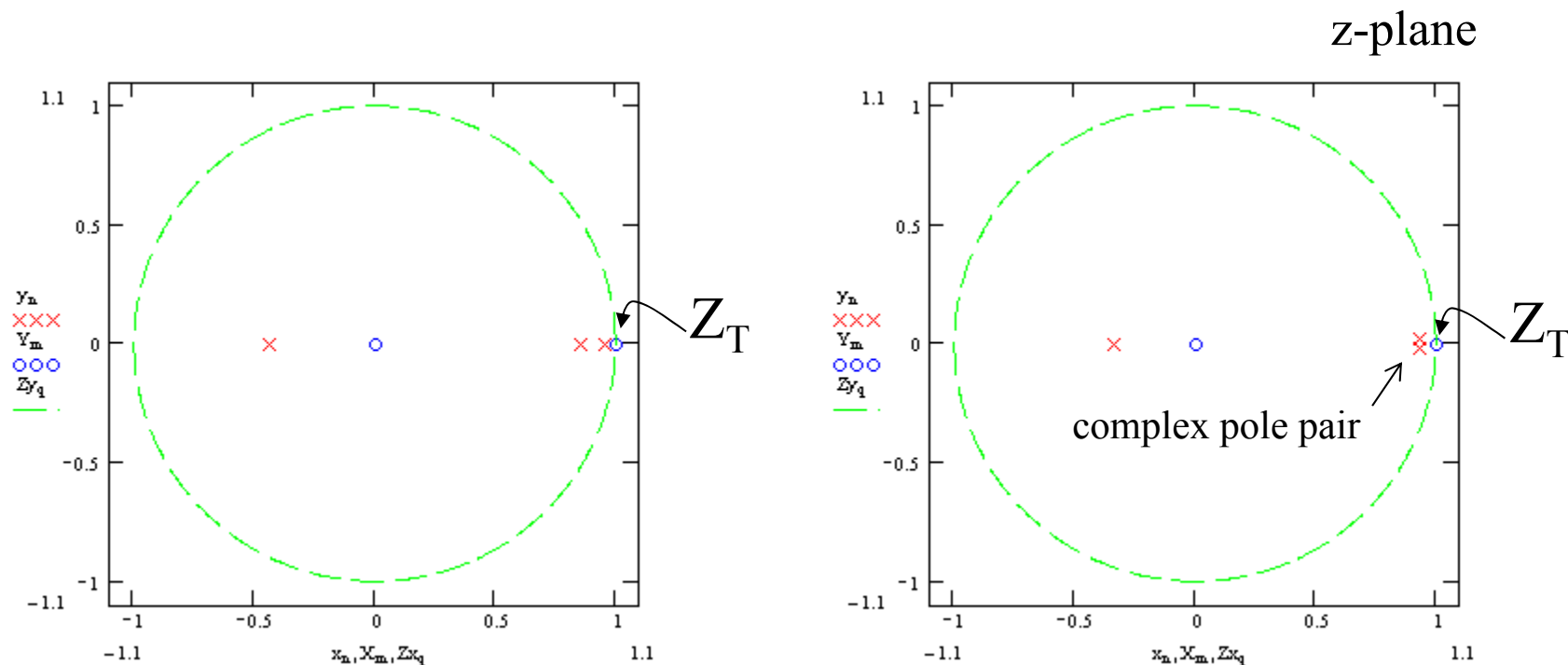
$T_{\text{chip}} = 6.5$  minutes

$T_{\text{sample}} = 4$  seconds

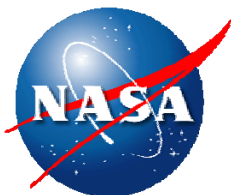


# FBG Poles and Zeros

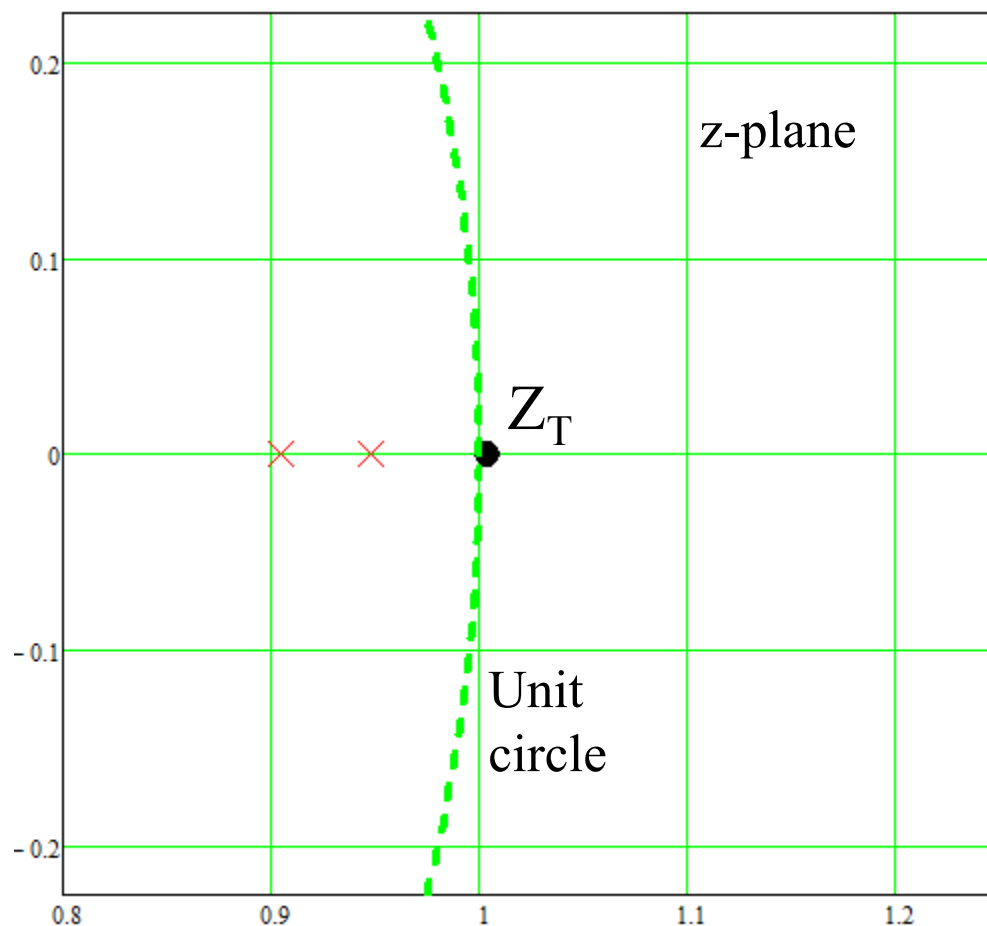
introducing the “thermality zero”,  $Z_T$



Context:  $T = 4$  seconds/sample, Modified Barker 7  
“dither” sequence,  $T_{\text{span}} = 6^\circ\text{C pp}$ .



# Dominant FBG Poles and Thermality zero, $Z_T$ (Detail)

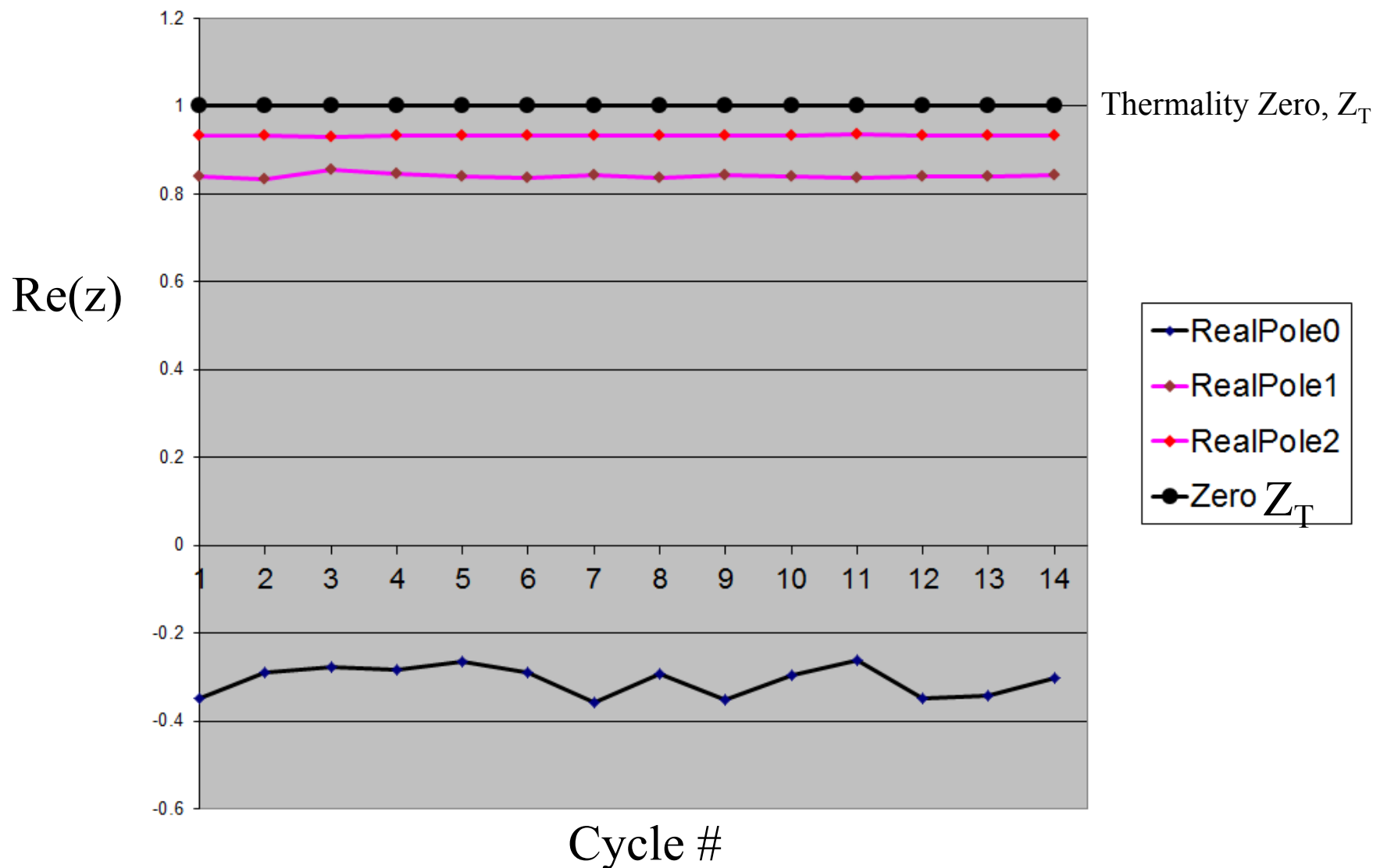






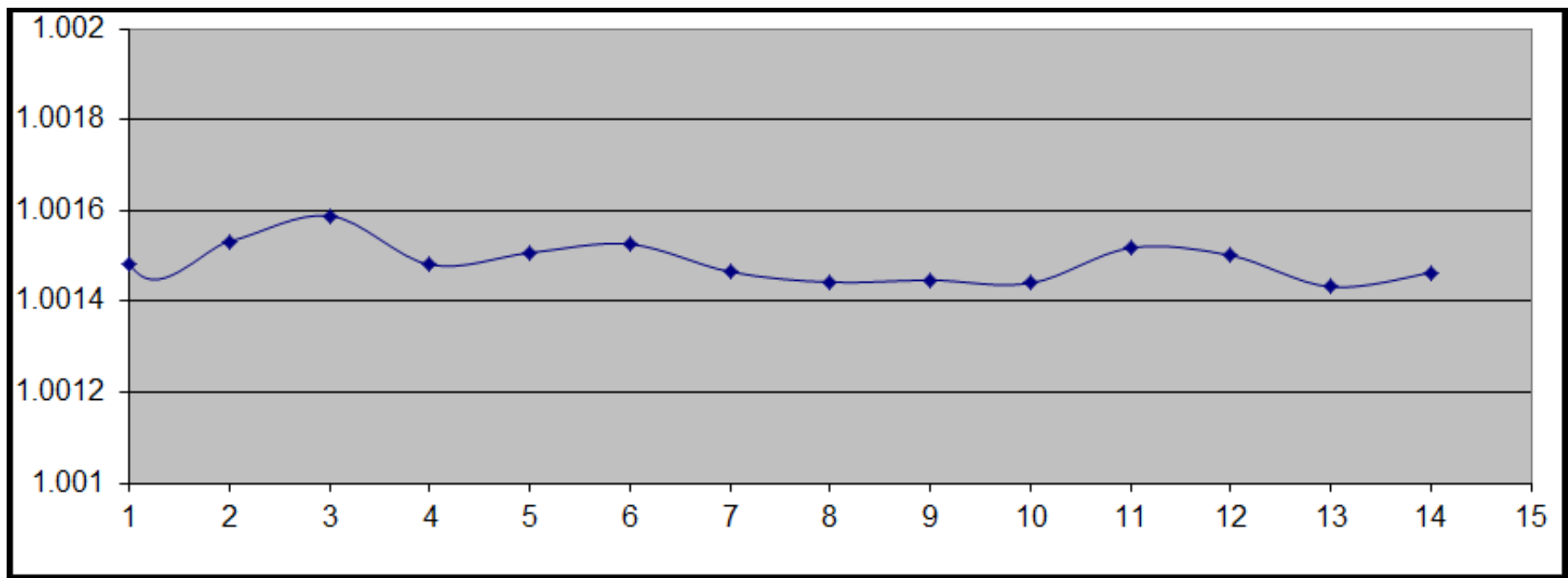
# Stability of the FBG AR3MA2 Parameters

Abscissa= #Barker 7 (B7) Thermal Cycles





# Stability of the FBG Thermality Zero, $Z_T$

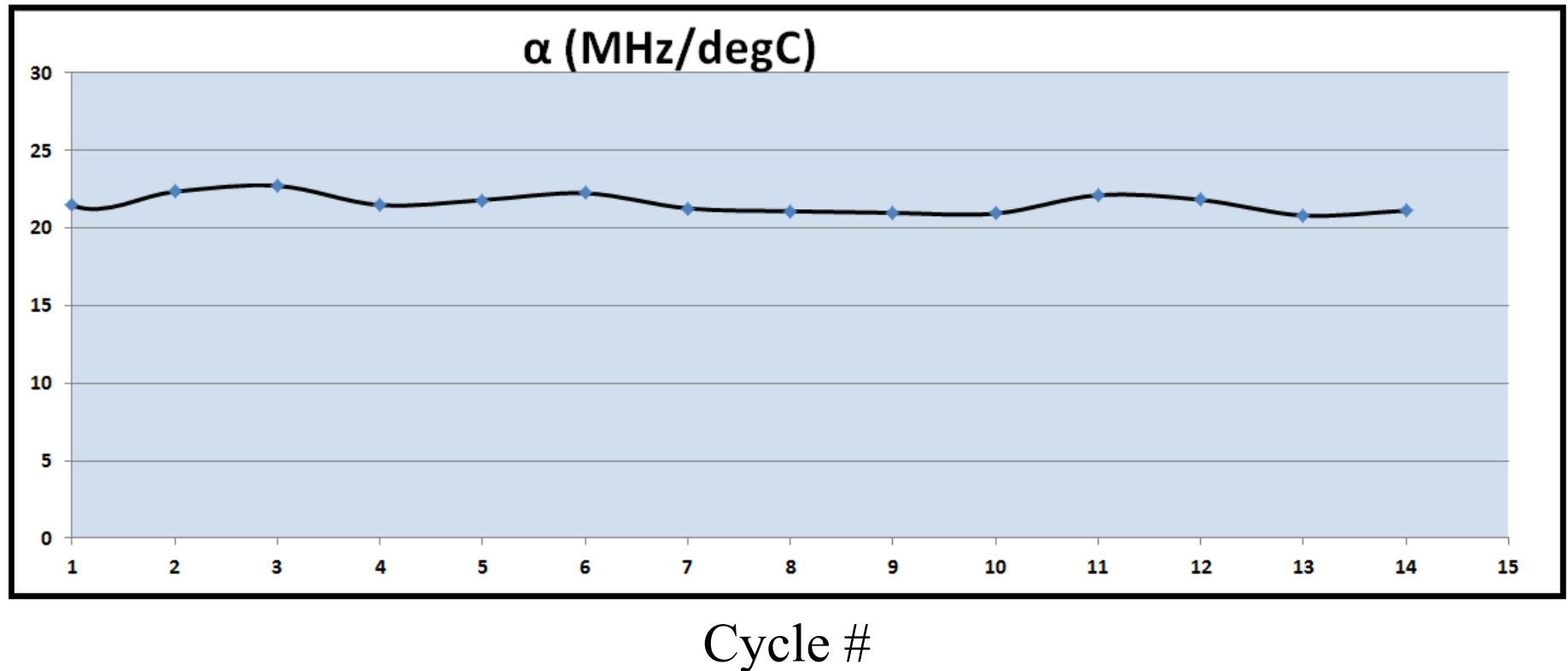


Cycle #

44 parts-per-million rms  
0.016% peak-to peak



# FBG Temperature Coefficient, $\alpha$



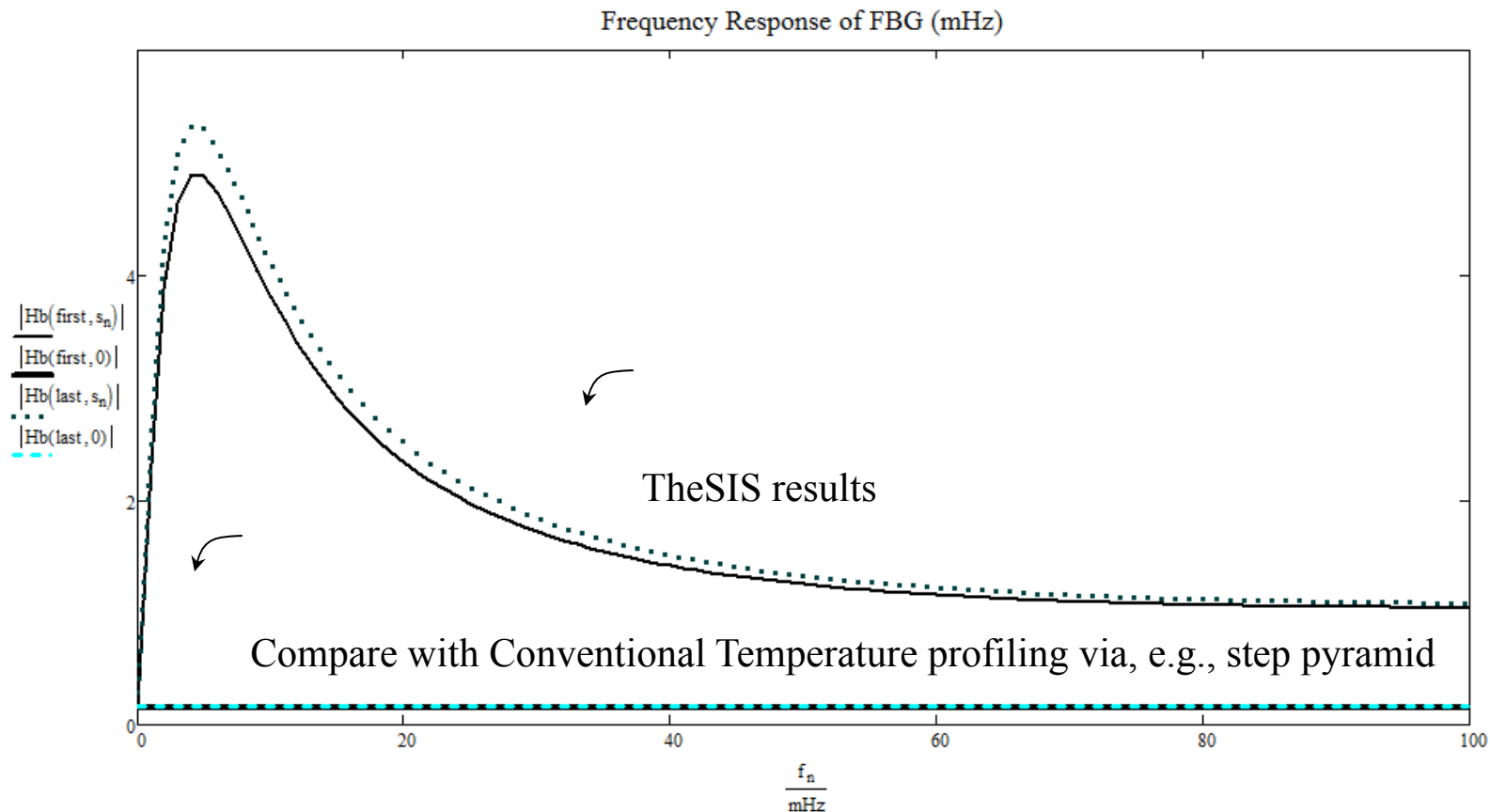
$$\alpha = \frac{\sum_{j=1}^{NMA} A_{j-1}}{1 - \sum_{i=1}^{NAR} B_i}$$

<3% variation rms (600 kHz/ $^{\circ}$ C)

<9% variation peak-to peak (1.9 MHz/ $^{\circ}$ C)



# Frequency Response Results



- Notes: 1) Mapped  $z$  plane to Laplace ( $s$ ) domain via the bilinear transform  
2) There is a 4 milliHz peak (4 minute period) to be aware of.



TheSIS FBGs.avi



# Multivariate Figure of Merit



## Example Target specification:

A perfectly athermal DUT with a parameter vector comprising a specified center wavelength and bandwidth.

**Example DUT response:** a DUT with a parameter vector comprising center wavelength, temperature coefficient, and bandwidth.

**Figure of Merit (FOM),** i.e. the expected performance over the observed range of environmental conditions, e.g. temperature deviations.

Note:  $\sigma_T$  represents a vector of parameters of the measured probability density function of temperature.

Note: the Spec and DUT parameter vectors can include insertion loss (IL); i.e. one can penalize deviations from a (IL) specified value.

$$\psi_{\text{req}}(\lambda, \sigma_{\text{req}}) := \left( \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma_{\text{req}}}} \cdot \exp\left(\frac{-\lambda^2}{2 \cdot \sigma_{\text{req}}^2}\right) \right)^{\frac{1}{2}} \quad \text{wavelength here is relative to specification}$$

$$\psi(\lambda, \lambda_c, \alpha, \sigma, T) := \left[ \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma}} \cdot \exp\left[\frac{-[\lambda - (\lambda_c + \alpha \cdot T)]^2}{2 \cdot \sigma^2}\right] \right]^{\frac{1}{2}} \quad \text{measured wavelength deviation from spec and temperature coefficient}$$

$$\text{FOM}(\lambda_c, \alpha, \sigma, \sigma_T) := \int_{-\frac{T_{\text{span}}}{2}}^{\frac{T_{\text{span}}}{2}} \left( \int_{-\frac{\lambda_{\text{span}}}{2}}^{\frac{\lambda_{\text{span}}}{2}} \psi(\lambda, \lambda_c, \alpha, \sigma, T) \cdot \psi_{\text{req}}(\lambda, \sigma_{\text{req}}) d\lambda \right)^2 \cdot \text{PDF}(T, \sigma_T) dT$$

Given a specification, optimize FOM as a function of any DUT, thermal parameter, or combinations thereof.

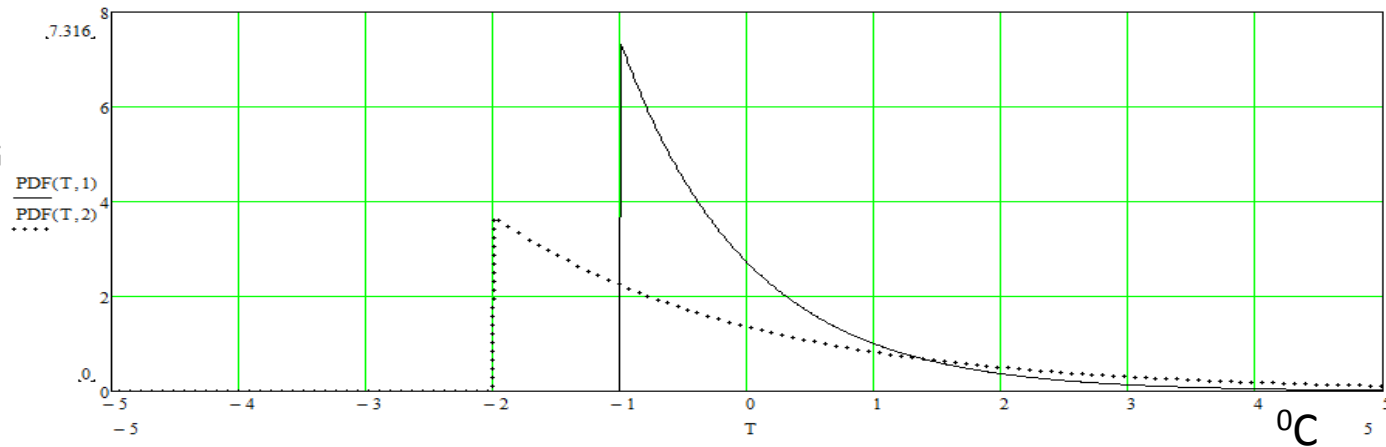


# Optimum Temperature Coefficient of Wavelength

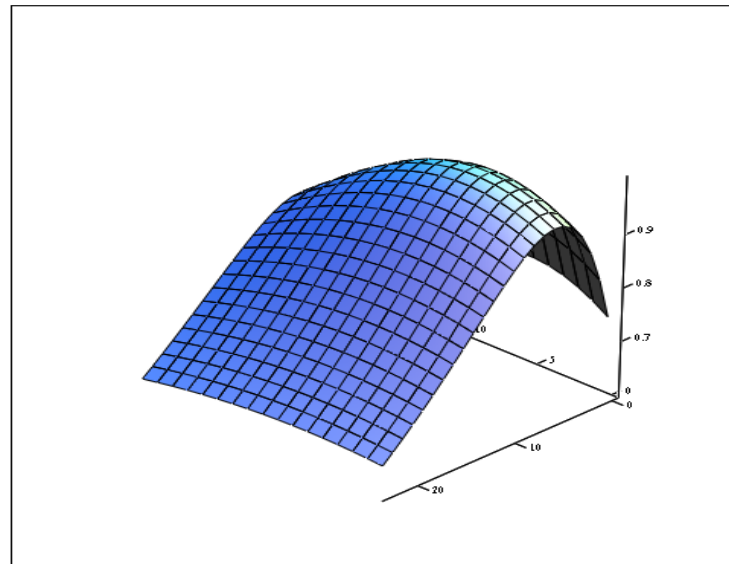
Example: Asymmetric Temperature Regulation



Probability  
density of  
regulated FBG  
temperature



**FOM Surface**  
(independent  
variables =  
wavelength offset  
and bandwidth)





# Summary

---



## Points & Highlights:

Demonstrated the use of spread spectrum temperature cycling to shorten test time.

Tested models using the AICc and extracted parameter vectors suitable for control loop design.

Introduced the idea of the “thermality zero”.

Presented a recursive algorithm that extracts multiple parameters of passive DUTs.

Showed 30 femtometer rms ( $1\sigma$ ) precision in measuring the center wavelength of passive optical components (FBGs).

Showed Model stability across multiple Barker 7 cycles: 2.8% rms cycle-to-cycle variation of thermal coefficient of FBGs (MHz/ $^{\circ}\text{C}$ )